# Application of active heat pulse method with fiber optic temperature sensing for estimation of wetting bulbs and water distribution in drip emitters

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*Keywords:*
Distributed temperature sensing (DTS)
Active heat pulse method with fiber optic temperature sensing (AHFO)
Wetting bulbs

A B S T R A C T

Through the use of the Distributed Fiber Optic Temperature Measurement (DFOT) method, it is possible to measure the temperature in small intervals (on the order of centimeters) for long distances (on the order of kilometers) with a high temporal frequency and great accuracy. The heat pulse method consists of applying a known amount of heat to the soil and monitoring the temperature evolution, which is primarily dependent on the soil moisture content. The use of both methods, which is called the active heat pulse method with fiber optic temperature sensing (AHFO), allows accurate soil moisture content measurements.

In order to experimentally study the wetting patterns, i.e. shape, size, and the water distribution, from a drip irrigation emitter, a soil column of 0.5 m of diameter and 0.6 m high was built. Inside the column, a fiber optic cable with a stainless steel sheath was placed forming three concentric helixes of diameters 0.2 m, 0.4 m and 0.6 m, leading to a 148 measurement point network. Before, during, and after the irrigation event, heat pulses were performed supplying electrical power of 20 W/m to the steel.

The soil moisture content was measured with a capacitive sensor in one location at depths of 0.1 m, 0.2 m, 0.3 m and 0.4 m during the irrigation. It was also determined by the gravimetric method in several locations and depths before and right after the irrigation.

The emitter bulb dimensions and shape evolution was satisfactorily measured during infiltration. Furthermore, some bulb's characteristics difficult to predict (e.g. preferential flow) were detected. The results point out that the AHFO is a useful tool to estimate the wetting pattern of drip irrigation emitters in soil columns and show a high potential for its use in the field.

## 1. Introduction

Measuring soil moisture content is important when irrigation uniformity is being studied. Many accurate methods exist for punctual measurement of soil water content; however, until recently, there were no precise "in situ" methods for the measurement of soil moisture content on large scales (meters to kilometers). This was a limitation when irrigation and hydrologic phenomena were studied.

Fiber optics have been widely used in telecommunications; a more recent application is in temperature measurement over long distances (up to 10 km) with a high temporal frequency. This use has opened a wide field of possibilities, which are very important in environmental monitoring (Freifeld et al., 2008; Selker et al., 2006a,b; Tyler et al., 2008; Westhoff et al., 2007). As a result, the measurement precision can reach ±0.2 °C in ±0.125 m.

The method used to determine the temperature is the "Distributed Fiber Optic Temperature Measurement" (DFOT). A laser pulse traveling through a fiber optic cable will result in Raman backscatter at two frequencies: Stokes (independent of $T$) and anti-Stokes (strongly dependent on $T$). $T$ can be inferred from the Stokes/anti-Stokes ratio and it is attributed to the position along the cable from which the light was reflected, computed from light-travel time.

This method has been used for the study of abandoned mines filtrations (Selker et al., 2006a) and the study of glaciers melting and small basins hydraulic balance (Selker et al., 2006b). Likewise, in porous media studies it has been successfully used in the detection of the seepage monitoring in dams (Perzlmaier et al., 2004, 2006) and water intrusion into landfill cap consisting of a vegetative soil barrier cover (Weiss, 2003).

The heat pulse method consists of applying a line source of energy to the soil with the resulting temperature fluctuation monitored by one or more parallel probes (Bristow et al., 1994). The rate of radial transmission of heat depends on many factors, such as the soil mineralogy, bulk density, particle shape, and mainly the soil moisture content (Shiozawa and Campbell, 1990). There have been studies of its usability in different soil textures and conditions. The temperature sensor can be placed inside the heat source (Bristow et al., 1994; de Vries and Peck, 1958; Shiozawa and Campbell, 1990) or it can consist of one or several sensors around the source (Bristow et al., 1993, 1994; Campbell et al., 1991; Jaeger, 1965; Larson, 1988; Lubimova et al., 1961).

Most authors using the heat pulse method focus, firstly, on determining the thermal properties of soil from the heat pulse response and then to relate these properties with the soil moisture content. However, other authors have been trying to relate the soil moisture content with the temperature increase during the heating process (Shaw and Baver, 1940; Youngs, 1956). The disadvantage of these last methods is that a specific calibration curve, relating temperature increase and soil moisture content, is needed for each soil type and sensor design.

Some objections are still brought up the accuracy of heat pulse methods regarding mineralogy, contact between sensor and soil, temperature sensibility and, principally, bulk density (Tarara and Ham, 1997).

Imhoff et al. (2006), in their review of soil moisture content measurement techniques, pointed out the active heat pulse method with fiber optic temperature sensing (AHFO method) as a powerful method to measure soil moisture content. It is a combination of both methods: the DFOT and the heat pulse method.

The AHFO method has been successfully used in the study of subsurface water movement (Perzlmaier et al., 2004, 2006) despite, until recently, measurements of soil moisture content were not very accurate. They could only distinguish between dry, wet and saturated soil (Perzlmaier et al., 2006; Weiss, 2003), without the possibility to measure small changes in soil moisture content (Weiss, 2003).

Recently, Sayde et al. (2010) have shown the feasibility of using AHFO in a sandy soil column to obtain accurate measurements within a wide range of soil moisture contents. The measurement error for volumetric soil water content was estimated lower than 5%. This result was obtained by defining the cumulative temperature increase $T_{cum}$ (°C s) as:

$$T_{cum} = \int_0^{t_0} \Delta T \, dt,$$

where $t_0$ (s) is the integration time and $\Delta T$ (°C) is the temperature increase with respect to the temperature right before the heat pulse. $T_{cum}$ depends on the soil's thermal properties and increases as $\theta$ decreases. At increasing heat capacity and thermal conductivity (which monotonically increase with soil water content), the rate at which heat is conducted away from the probe increases. Consequently, the integral $T_{cum}$ is reduced for sufficiently long heat pulses. Thus, assuming that water flow is negligible, a function relating $T_{cum}$ to $\theta$ holds for a given soil, heating rate, integration time, and fiber optic cable characteristics.

The objective of this paper is to study, in a soil column, the ability of the AHFO method to estimate the shape and size of wetting patterns from a drip irrigation emitter and to measure water distribution during irrigation.

## 2. Materials and methods

### 2.1. Experimental procedure

The DTS (Distributed Temperature Sensor) (Fig. 1) used in the experiments (Ultima004 – Silixa LDT) is capable of measuring with a high time frequency (1 s) and of determining temperature every 0.125 m along the fiber optic cable. For the experiment, a Plexiglas column was built with a hexagonal base having diagonal of 1 m and a height of 0.6 m (Fig. 1). The column base had small perforations (6 mm of diameter), so water could drain freely from the bottom.

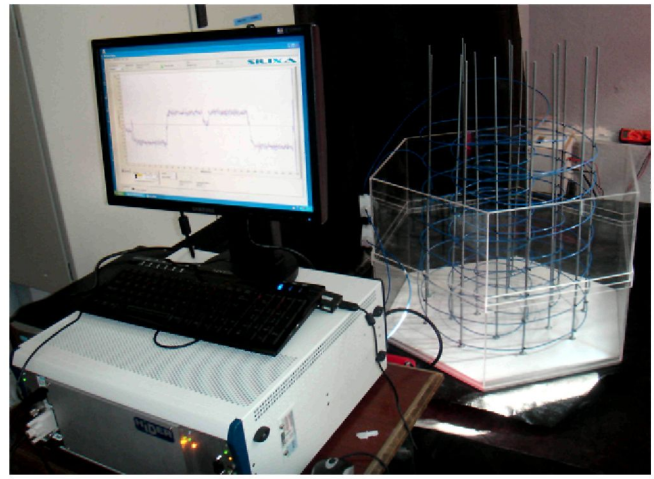

**Fig. 1.** DTS and column.

Inside the column, fiber optic cable was coiled, forming three concentric helixes with diameters of 0.2 m, 0.4 m and 0.6 m (Fig. 2) with spacing of 0.10 m between turns.

After placing the helixes, the column was filled with soil which was collected from an experimental field. This field is plowed at least once a year.

The experiments were planned to be performed in a homogenous porous media. As such, it was extracted from a range of depths from 10 to 40 cm. To determine the texture of the soil, samples were taken in different locations and at several depths within the afore-

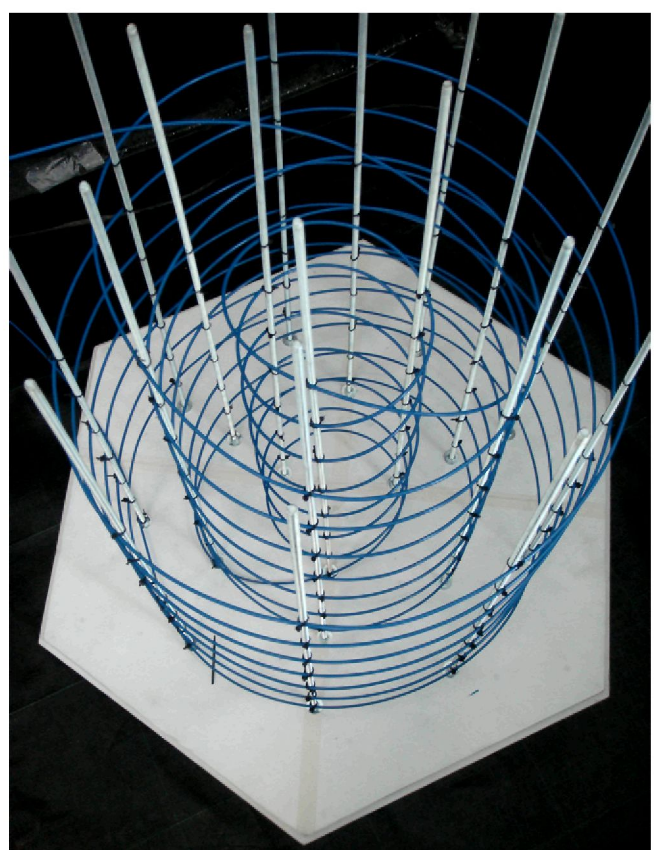

**Fig. 2.** Fiber optics helixes.

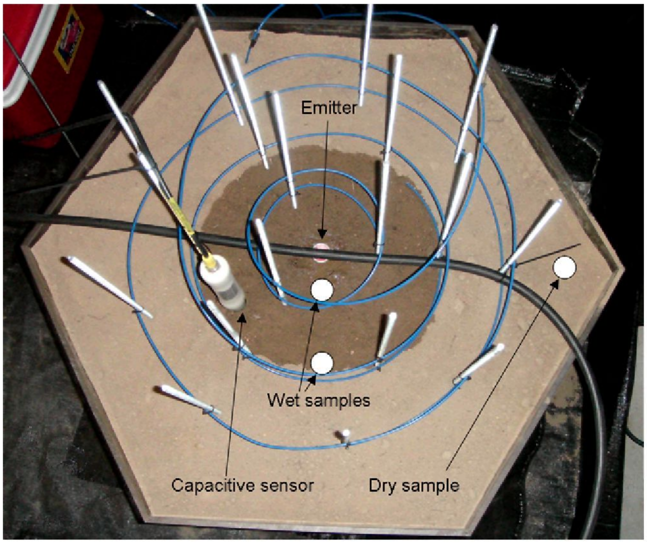


**Fig. 3.** Location of emitter, capacitive sensor and gravimetric samples.

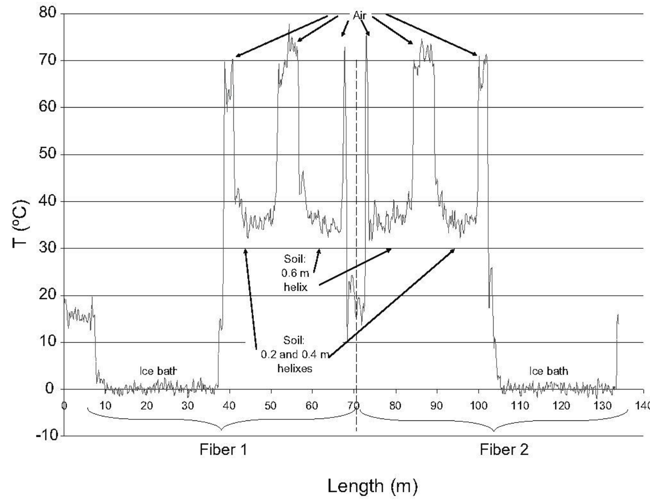


**Fig. 4.** Temperatures measured along the fiber during a heat pulse.

mentioned range. The percentages of sand, silt and clay equal to 63.5%, 28.6% and 6.1% were determined by densimetry. According to USDA the soil can be classified as sandy loam.

The most homogeneous bulk density possible was desired. To achieve the bulk density measured within the field, approximately 1500 kg/m$^3$, the soil was placed into the column in controlled lifts. A determined weight of soil (measured with a scale of precision ± 0.1 kg) was placed in the column. Then it was compacted applying pressure with a small circular compactor until the lift had the corresponding height. In this way, it was possible to control the volume occupied by the weight of soil established according to the fixed bulk density.

Unfortunately, as it will be discussed in the results, this method adopted to fill the column had the disadvantage to create a discontinuity between the soil layers, determining, consequently, horizontal preferential flow.

Saturated water content $\theta_s$ (cm$^3$ cm$^{-3}$), as determined by the gravimetric method was 0.36 (m$^3$/m$^3$). A pressure compensating emitter having nominal discharge of 2 L s$^{-1}$ was installed in a PE pipe (Fig. 3). It worked at constant pressure of 10 m and water was continuously applied for 5 hours and 40 minutes. During the test, the temperature was measured and recorded with the DTS unit every 2 s.

The selected cable was composed of four fiber optical fibers covered with a central stainless steel capillary, surrounded by stainless steel strands, and finally enclosed in a protective nylon jacket. The metal components were used as an electrical resistance heater (0.365 Ω/m) with electric power of 20 W/m applied to perform the heat pulses. This power was controlled by a transformer.

The heated part of the cable was 31 m long, of which 20 m were buried (Fig. 4), comprising a 148 measuring points, developing a three-dimensional network within the soil. Both the fibers ends were connected, so the laser circulated along the circuit two times. In this way, temperature values of each section were measured two times and averaged in order to obtain more accurate data.

To calibrate the DTS unit, 30 m of the unburied cable, were placed into an ice bath containing liquid water and ice and it was frequently stirred, to assure a steady temperature of 0 °C with no stratification. Given the cable layout and design, the laser traveled twice along the 30 m of cable resulting in two cold sections, at the beginning and at the end (Fig. 4). In this way, it was possible to determine the offset and the slope of DTS calibration equation.

In order to obtain accurate data, it is essential to have an accurate control of pulse duration. As such, a digital timer with ±0.01% precision was programmed to perform 2 minute long pulses every 20 minutes. A total of 21 heat pulses were launched and analyzed: 4 under dry conditions before irrigation (that were averaged), 16 during irrigation, and 1 right after irrigation.

For the gravimetric determination of soil moisture content, dry soil samples were collected with a drill before irrigation at one location along the soil (Fig. 3). Similarly, wet soil samples were collected after the experiment in two different locations: one close to the 0.2 m diameter helix and the other next to the 0.40 m diameter helix (Fig. 3). Gravimetric soil water contests were obtained in laboratory by a moisture analyzer (IR35, Denver Instruments).

Additionally, soil moisture content was continuously monitored in between the first and second helixes (Fig. 3) with a capacitive sensor (Profile probe PR2 – ΔT Devices Ltd.) allowing to measure the volumetric soil moisture content at depths of 0.10 m, 0.2 m, 0.3 m and 0.40 m. The sensor was initially calibrated in laboratory in a small soil column, using the same soil and conditions (used in the big experimental soil column). Data were recorded by means of a data acquisition card in a computer every 3 s. During the experiment, measurements acquired with the sensor were used to monitor the wetting front position.

### 2.2. *Data processing*

Temperature data set recorded by the DTS was processed to determine the value of $T_{cum}$ from the three helixes. Temporal evolution of temperature in each fiber point was investigated. Once the heat pulses were localized within the data, they were extracted in order to obtain, at any point of the fiber, the evolution of temperature during the heat pulse. In this study, the heating phase of the pulse (120 s) was taken into account to calculate the value of $T_{cum}$.

In order to achieve an accurate value of the initial temperature, the temperature data corresponding to 300 s before starting the pulse were averaged. This average was subtracted from the temperature during the pulse, obtaining the temperature increase $\Delta T$. Then, $T_{cum}$ was calculated as the sum of the values obtained by multiplying $\Delta T$ by the time interval between measurements.

### 2.3. *$T_{cum}$–$\theta$ calibration curve*

The value of $\theta$ from the gravimetric samples was compared with the value of $T_{cum}$ at that exact position. In order to obtain the

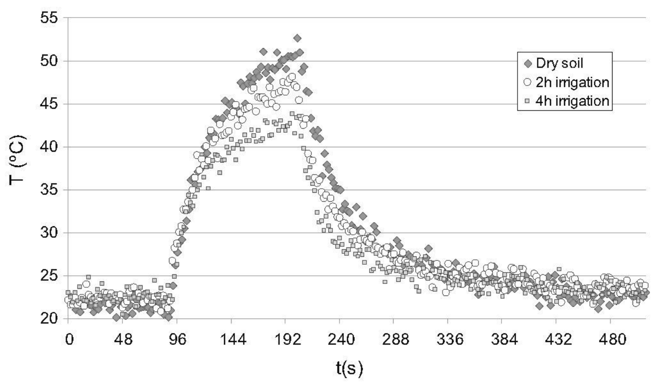


**Fig. 5.** Examples of heat pulses.

calibration curve an exponential expression was fitted, by using the least squares method.

Despite the possible differences in bulk density along the soil profile, only one calibration curve was considered. However, it is important to point out that this is valid for the investigated soil and conditions. In the field, different calibration curves might be necessary if the soil is heterogeneous so that a single calibration curve could produce significant errors.

### 2.4. Wetting patterns

Once obtained the calibration curve, the values of $\theta$ were computed for all the measuring points. In order to identify the wetting pattern resulting from the irrigation event, the position in the column of each data point was set. Thus, the depth and the distance from the center of the soil column (where the emitter was placed) were considered. Note that a symmetrical wetting bulb was assumed.

For representing the wetting bulb, two difficulties arose. Firstly, the fiber length was longer in the larger helix turns than in the smaller helix turns. Secondly, considering the distance to the center of the column, there were only 3 sets of data, one at 0.1 m, the second at 0.2 m, and the third at 0.3 m. These drawbacks were overcome by linear interpolation in order to complete the missing values.

## 3. Results and discussion

Fig. 5 shows, for one measurement point in the fiber, the evolution of temperature over time of three heat pulses acquired at different times before and after starting irrigation. As expected, the increase of temperature and the soil moisture content has an inverse relationship: the higher the soil moisture content $\theta$ the lower the temperature during heating. Thus, as explained later, the area underneath the curve from the initial temperature (integral), which is precisely $T_{cum}$, tends to decrease when values of $\theta$ increase.

Figs. 6 and 7 allow the comparison along the soil profile of $T_{cum}$ (Figs. 6a and 7a) and $\theta$ measured by gravimetry (Figs. 6b and 7b) before and after the irrigation event, respectively. As expected, an inverse correlation is observed (see figures a and b in both situations).

Before irrigation (Fig. 6), differences in soil water content along the soil profile were very small. Measured soil moisture content was slightly higher at the column bottom than on the top, and it was even higher between 0.35 and 0.55 m in depth. Before carrying out the test, the soil stayed in the column for two weeks and lost some of the initial water content that it had when the column was originally filled. This effect was more pronounced in soil layers near the top and the bottom surfaces.

These small differences in soil water content were detected by the fiber used in the experiment. The most similar shape of the evolution of $T_{cum}$ with depth corresponds to the 0.6 m diameter helix, that was the nearest sampled profile.

The final wetting bulbs after the irrigation event can be observed in Fig. 7. As expected, an increase of soil water contents (compared to the initial values before irrigation) is observed between the top surface and about 40 cm depth. Values of $\theta$ ranged from, approximately 0.1 $m^3/m^3$ in the drier portions, to 0.31 $m^3/m^3$, in the wetter portions. The wetting front reached approximately a depth of 0.35 m.

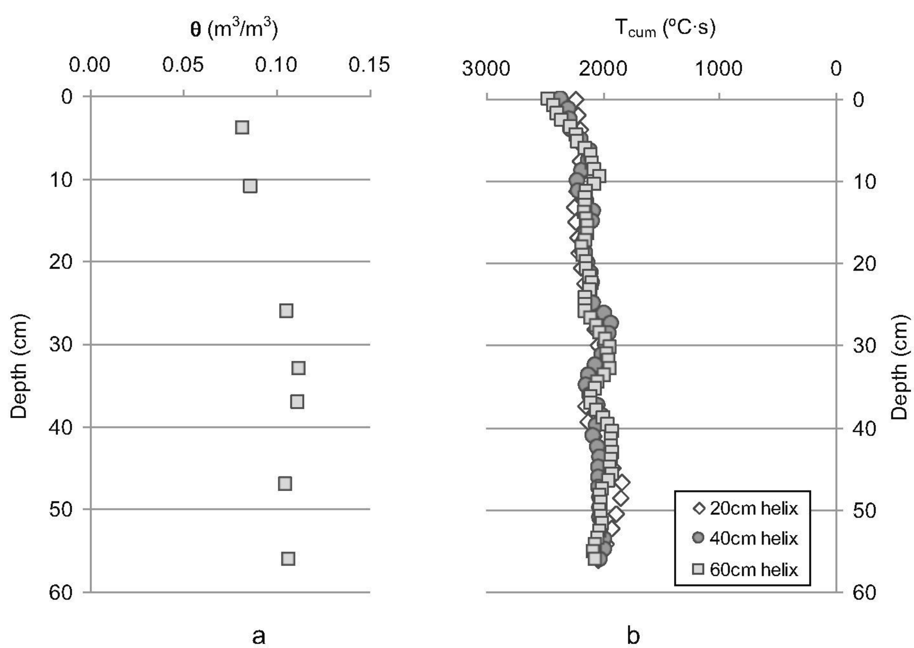


**Fig. 6.** Conditions before the irrigation event. (a) $\theta$ variation with depth. (b) $T_{cum}$ variation with depth.

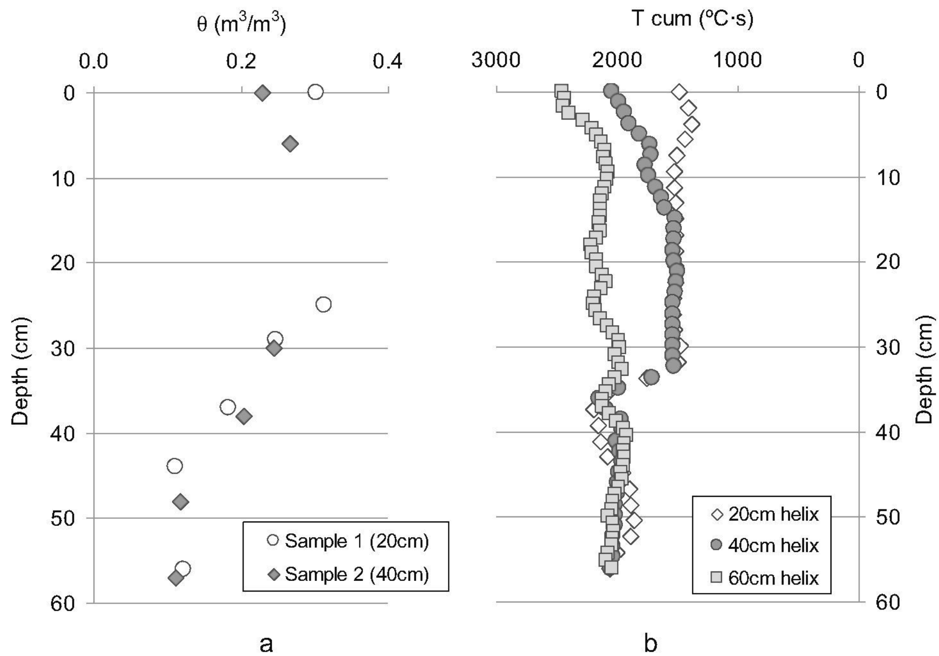


**Fig. 7.** Conditions after the irrigation event. (a) $\theta$ variation with depth. (b) $T_{cum}$ variation with depth.

Soil water contests acquired with the capacitive sensor confirmed that the wetting front during the irrigation, reaches its maximum depth was somewhere between 0.3 and 0.4 m.

The $\theta$ values after irrigation showed a good fitting with $T_{cum}$ values at the same depths and time in the 0.2 m and 0.4 m diameter helixes (placed close to where the soil samples were collected).

As explained, no soil was sampled close to the 0.60 m diameter helix. $T_{cum}$ values of this helix showed very small differences in soil water content. Thus, it can be assumed that the wetting bulb did not reach that portion of soil.

Fig. 8 shows the calibration curve for the studied interval. As explained in the previous section, the values of $T_{cum}$ and $\theta$ were fitted with the following exponential relationship: $\theta = 3.2 \pm 0.3e^{0.00165T_{cum} \pm 0.00003}$, $R^2 = 0.9937$. The relative error caused by the use of this relationship was estimated in about 6%.

With the $\theta$ ($T_{cum}$) relationship, the temporal evolution of soil moisture content in each point of the soil and heat pulse was determined. Dimensions and shapes of wetting areas for five different irrigation times are shown in Fig. 9. The radius of wetted bulb was a bit smaller than 0.3 m and its height was around 0.35 m. While the purpose of this work was not the study the bulb shape, but the method's capability of measuring it, some observations will be made.

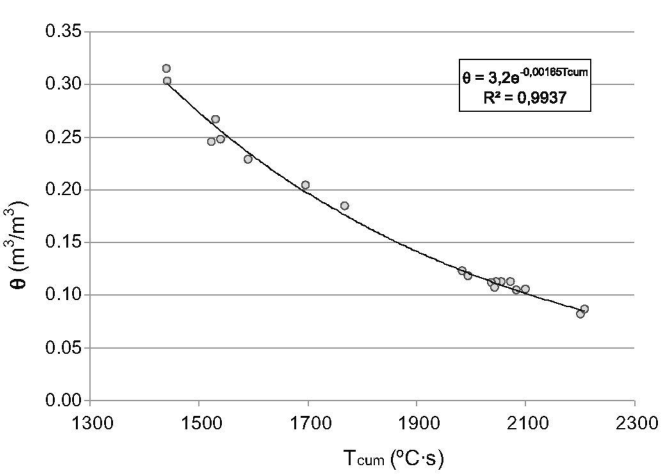


**Fig. 8.** $T_{cum}$–$\theta$ relationship.

In the simulations initial water content was, as measured gravimetrically, quite uniform throughout the column. However at 0.35–0.55 m of depth, the soil moisture content was slightly higher.

The wetting bulb did not present the shape expected. As observed in Fig. 9, horizontal movement of water was more pronounced than expected. This could be explained by the method used to fill the column. As explained in the previous section, the soil was introduced in lifts and compacted applying vertical pressure, which probably produced preferential flow in the horizontal direction. The areas of preferential flow seem to follow a pattern and appear to be separated at a constant distance, resembling the lifts.

The lifts suggest possible small differences in bulk densities in the column as a source of error. Nevertheless, the compaction differences would not explain this performance. Firstly, the soil moisture content has been pointed out as the crucial factor for the differences in temperature increase during a heat pulse over other factors such as bulk density and those mentioned in Section 1. Secondly, the influence of the lifts is not observed in the soil before irrigation. Finally, the effect of bulk density would be the opposite of the one observed in the column: the soil moisture seems to be higher in the central part of the lifts, which are supposed to be the less compacted parts (lower bulk density). However, a smaller bulk density would lead to a larger $T_{cum}$, which, converted to $\theta$ by the relation determined earlier, would mean a lower soil moisture content.

In future studies, other filling method will be used. For example, compacting by vibration instead of that by pressure could help solve these drawbacks.

The evolution of bulb dimensions in surface matched the represented bulbs. It stabilized after three hours with a maximum diameter or, approximately 0.4 m (Fig. 3).

No saturated region was detected but it should be noticed that there is a lack of information in corresponding to a radius of 0.10 m from the emitter and the relative soil water contents were estimated by extrapolation.

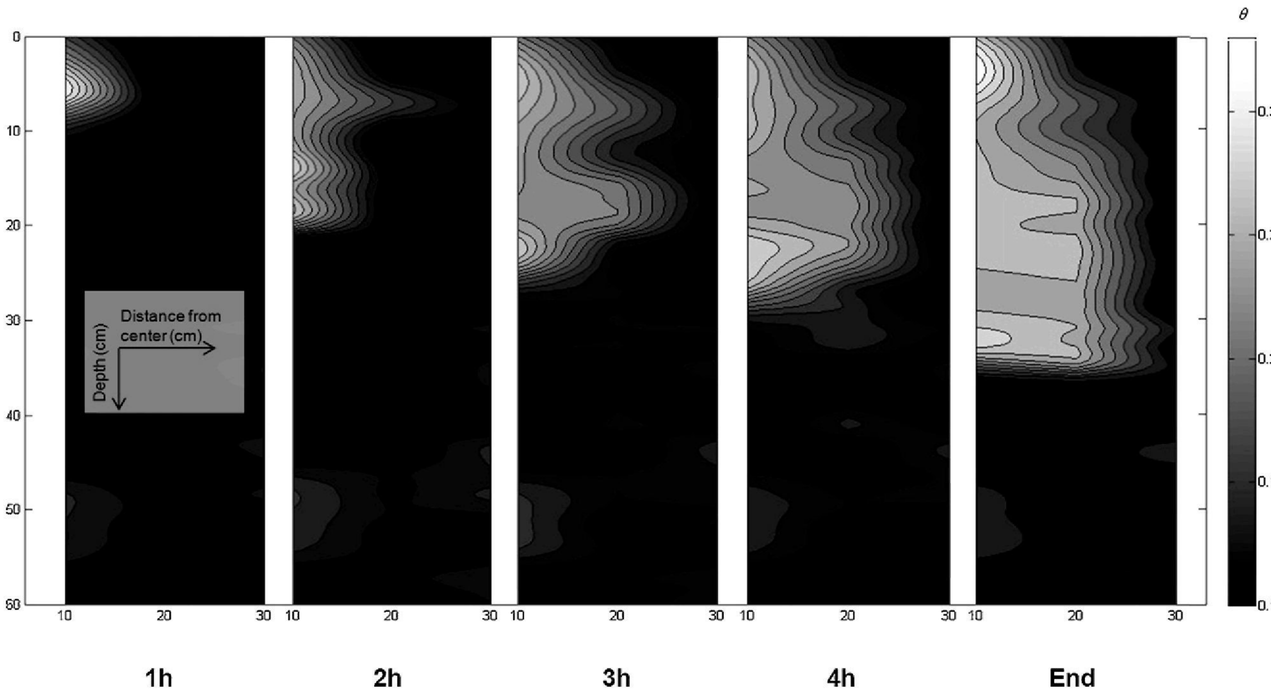


**Fig. 9.** Distribution of $\theta$ in the wetted bulbs during irrigation.

Despite the discussed problems it can be concluded that the AHFO method allowed a satisfactory prediction of the shape of wetting bulb and the gradients of soil water content distribution in a homogeneous porous media in prepared laboratory. Nevertheless, field measurements are expected to have additional uncertainty, mainly caused by the soil spatial variability and by a possible poor contact between the fiber and the soil.

## 4. Conclusions

Soil water content $\theta$ in loamy soil column could be satisfactorily predicted by measuring the temperature of the soil profile. Univocal relationship between $\theta$ and the thermal integral $T_{cum}$, corresponding to the heating phase of the heat pulse, was determined. Heat pulses were applied during irrigation. Temperatures recorded along the fiber, allowed finally estimate soil water contents along the soil profile.

The AHFO method shows a potential to study the movement of water around a drip irrigation emitter in relatively homogeneous soil columns. It clearly allows distinguishing the shape and dimensions of the wetted bulb. These variables are needed in selecting irrigation design variables, such as emitters and laterals spacings, and in operation variables such as irrigation time. Moreover, other information, difficult to predict, could be detected the proposed methodology, like preferential flow, horizontal movement of the water, etc.

These findings encourage to proceed with the application of the AHFO under field conditions, although some further efforts in developing the method are necessary, especially in order to consider the influence of soil spatial variability.

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